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Optimal energy control modelling of a vertical shaft impact crushing process

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Abstract

This paper presents an optimal control model to improve the operation efficiency of a vertical shaft impact (VSI) crushing process. The optimal control model takes the energy cost as the performance index to be minimized by accounting for the time-of-use (TOU) tariff. The control variables in the developed model are the belt conveyor feed flow rate, the VSI crusher rotor feed rate and the bi-flow or cascade flow rate. The effectiveness of the developed model is shown through the simulation results of the crushing process in a coal-fired power plant.

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Keywords: Vertical shaft impact crusher; Modelling; Energy; Optimal control; Time-of-use tariff.

1. Introduction

Vertical shaft impact (VSI) crushers are usually used in tertiary crushing station of both aggregate and mining industries for crushing of hard rock material or ores when a product material with cubical shape and large amount of fines is required [1, 2]. VSI crusher has been also shown to be one of the best options with comparison to other secondary and tertiary crushing machines such as cone crushers, due to its higher energy efficiency [1]. This therefore leads to a relatively lower operational energy cost of this crushing machine. However, more energy cost reduction or saving can be achieved when optimal operation control is applied to this process based on time-of-use (TOU) electricity tariff.

Several research works have been conducted to deal with the operation efficiency control of material handling equipment in mining industries based on TOU tariff. Research papers such as [3, 4] investigated the optimal control strategies of belt conveyor systems for coal mining industries in order to achieve minimal energy cost. In [5], an optimal control strategy has been studied for the optimal hoist scheduling of a deep level mine twin rock winder system.

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However, there have been relatively very few research works undertaken in the area of energy cost optimization of comminution processes (crushing and grinding).

The effort of this paper therefore is to establish a model for optimal energy control strategy that minimizes the energy cost associated with the operation of VSI crushing process. The optimal control model takes into account of the TOU tariff and other system limitations as constraints. A case study is given and the effectiveness of the developed control strategy is shown through the simulation results.

2. Optimal energy control model of a VSI crushing system

2.1. System description

The operating principle of the VSI crusher is given [1, 2, 6, 7]. The ore/rock material falls vertically into the rotor through the feed hopper and then accelerated to an edge speed of the high-speed rotor of about 50-85m/s, before being projected to the surrounding bed of rock formed during operation. However, during operation, a fraction of material does not pass through the rotor, and this is commonly referred to as cascade flow or bi-flow. For this reason, the cascade flow or bi-flow material does not theoretically participate to the energy consumption of VSI crusher.

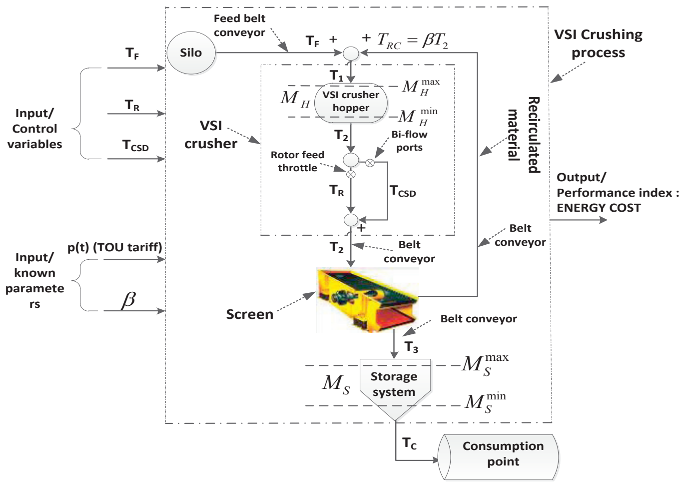

Figure 1: Schematic of a tertiary mining VSI crushing station (adapted from [1])

A typical VSI crushing station with closed circuit is shown in Figure 1. In this figure, T_F denotes the belt conveyor feed flow rate, T_{RC} is the recirculated material flow rate, T_1 is the mass flow rate into the VSI crusher hopper, T_2 is the mass flow rate from the VSI crusher hopper, T_{CSD} is the bi-flow or cascade flow rate[1], T_R is the flow rate through the VSI crusher rotor, T_3 is the mass flow rate from the screening device, and T_C is the mass flow rate of crushed material consumption. M_H and M_S are respectively, the material mass available in the VSI crusher hopper and storage system, while the superscripts "*min*" and "*max*" denote, respectively, their minimum and maximum limits. β denotes the recirculating mass flow ratio.

2.2. Objective function and system constraints

The optimal energy control model of a VSI crusher has been developed is in discrete-time domain as

$$\min \; J_C = t_S \frac{1}{\eta} \sum_{j=1}^{N_s} \left(R^2 \omega_{mcr}^2 T_{R_j} + P_{mcr,0} \right) p_j \tag{1}$$

subject to

$$\begin{cases} T_F^{\min} \le T_{F_j} \le T_F^{\max}, & (1 \le j \le N_S), \\ T_R^{\min} \le T_{R_j} \le T_R^{\max}, & (1 \le j \le N_S), \\ T_{CSD}^{\min} \le T_{CSD_j} \le T_{CSD}^{\max}, & (1 \le j \le N_S), \end{cases} \tag{2}$$

$$\begin{cases} T_1^{\min} \le T_{F_j} + \beta_j \left(T_{R_j} + T_{CSD_j}\right) \le T_1^{\max}, & (1 \le j \le N_S), \\ T_2^{\min} \le \left(T_{R_j} + T_{CSD_j}\right) \le T_2^{\max}, & (1 \le j \le N_S), \\ T_3^{\min} \le \left(1 - \beta_j\right)\left(T_{R_j} + T_{CSD_j}\right) \le T_3^{\max}, & (1 \le j \le N_S), \\ T_{RC}^{\min} \le \beta_j \left(T_{R_j} + T_{CSD_j}\right) \le T_{RC}^{\max}, & (1 \le j \le N_S), \\ \alpha_{CSD}^{\min} \le \dfrac{T_{CSD_j}}{T_{R_j} + T_{CSD_j}} \le \alpha_{CSD}^{\max}, & (1 \le j \le N_S), \end{cases} \tag{3}$$

$$\begin{cases} M_H^{\min} \le M_{H,0} + t_s \sum_{i=1}^{j} \left[T_{F_i} + (\beta_i - 1)\left(T_{R_i} + T_{CSD_i}\right)\right] \le M_H^{\max}, & (1 \le j \le N_S), \\ M_S^{\min} \le M_{S,0} + t_s \sum_{i=1}^{j} \left[(1 - \beta_i)\left(T_{R_i} + T_{CSD_i}\right) - T_{C_i}\right] \le M_S^{\max}, & (1 \le j \le N_S), \end{cases} \tag{4}$$

$$\sum_{j=1}^{N_S} \left(1 - \beta_j\right)\left(T_{R_j} + T_{CSD_j}\right) t_s \ge \sum_{j=1}^{N_S} T_{C_j} t_s. \tag{5}$$

In the model given by equations (1)-(5), the control or decision variables are T_R, which is the flow rate through the VSI crusher, the belt conveyor feed rate T_F, and the cascade flow rate T_{CSD}. The rotor speed ω_{mcr} of the VSI crusher is taken to be constant. The dependent variables are the other mass flow rates such as T_1, T_2, T_3 and T_{RC}, but also the state of the stored mass of material, M_H and M_S. The cascade ratio α_{CSD} is also regarded as dependent variable. The recirculated ratio β and the material consumption flow rate T_C are uncontrollable but are assumed to be predictable.

$R(m)$ is the rotor radius of the VSI crusher, and $P_{mcr,0}$(W) is the no-load mechanical power of VSI crusher. N_s is the sample number, j is the j^{th} sampling interval, $t_s=(t_f-t_0)/N_s$ is the sampling period within the control horizon $[t_0, t_f]$, and p_j is the electricity price assumed constant at the j^{th} sampling interval. $M_{H,0}$ and $M_{S,0}$ are respectively, the initial stored mass of material in the VSI crusher hopper and storage system

Equation (1) denotes the total energy cost of VSI crusher, derived from specific energy model given in [6]. Equation (5) is a constraint standing for production requirement.

3. Current control strategy of a VSI crushing process

Practically, the VSI crushing process operates continuously, while the flow rates are adjusted in such a way to meet the system constraints and achieve the plant production requirement. Hence, the current control strategy is formulated as an optimal control problem with the objective function being the quadratic deviation between the total actual plant production and the total plant requirement. This is given as:

$$\min \ J_{PR} = \left(\sum_{j=1}^{N_S} \left(1 - \beta_j\right)\left(T_{R_j} + T_{CSD_j}\right) t_s - \sum_{j=1}^{N_s} T_{C_j} t_s \right)^2, \tag{6}$$

subject to constraints (2)-(5).

4. Case study and simulation results

The coal crusher present in the conveying system, given in [3] was not included in the optimal energy control problem since it was stated that it follows its own optimal control strategy. In this work, the coal crusher in [3] is assumed to be a VSI crushing machine and the same system is used in this work. A *600kW* (*800hp*) Barmac B9100SE VSI crusher is used for simulation with no recirculating material (β=0). 2013/2014 Eskom Megaflex for high demand season weekday is used as TOU tariff. Since the optimal energy control model is a linear optimization problem (both objective function and constraints are linear), the *linprog* function of Matlab 2013 Optimization Toolbox is used to solve the problem. The objective function of the current control strategy is a quadratic function with all constraints being linear. Hence, the *quadprog* function of Matlab 2013 Optimization Toolbox is used. A sampling period of *10min* and control horizon of *24h* are used.

As can be seen from Figure 2, with the current control strategy, the crushing station will run at almost a constant flow rate without shifting the load out of peak period. On the other hand, with the optimal energy control scheme as shown from Figure 3, the load is shifted from peak period to off-peak and standard periods in order to reduce the energy cost. It can be seen from Figure 3 that a bigger amount of load is shifted to off-peak period than standard period due to the cheaper energy cost. Note that the dotted lines in Figures 2 and 3 denote lower and upper limits of the corresponding variable. From the simulation results, a cost saving of about 21.80 % is achieved. The optimal energy control approach developed in this paper can also be applied to other applications such as pumping storage systems, manufacturing processes with buffer storage systems, where the TOU electricity tariff is used.

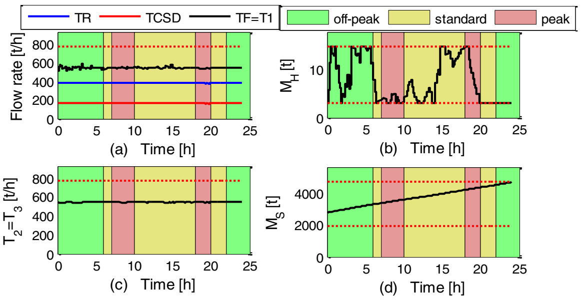

Figure 2: Current control strategy

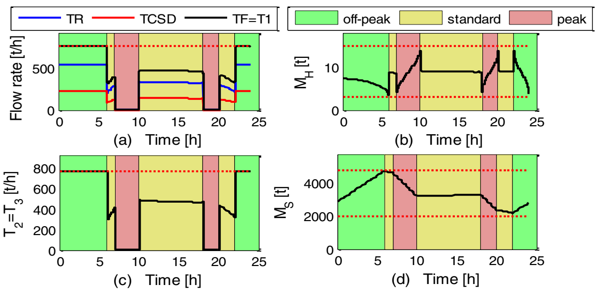

Figure 3: Optimal energy control strategy

5. Conclusion

A model for optimal energy control of a VSI crushing process is developed in this paper. The simulation results show the potential of energy cost saving in a VSI crushing station, based on TOU tariff.

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